Secondary cavitation due to interaction of a collapsing bubble with a rising free surface

著者	小玉　哲也
journal or publication title	Applied Physics Letters
volume	59
number	3
page range	274-276
year	1991
URL	http://hdl.handle.net/10097/47464

doi: 10.1063/1.105619

Secondary cavitation due to interaction of a collapsing bubble with a rising free surface

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(Received 4 February 1991; accepted for publication 18 April 1991)

An experimental investigation was made of the motion of a cavitation bubble in the vicinity of a free surface in order to study an induced secondary cavitation during the bubble rebound. A bubble was produced by focusing a ruby laser into water, and its subsequent behavior was observed with a high-speed camera. The deformable nature of both a bubble and a free surface becomes significant as the mutual distance between them is decreased. Immediately after bubble rebound, a secondary cavitation occurs at around zero dynamic pressure region which is developed in water between a rising free surface and a collapsing bubble, due to the local pressure reduction mainly caused by the interaction of expansion waves originated from the surface.

The motion of a bubble near a free surface has been investigated in the field of underwater explosion for a long time.[1,2] A field experiment showed that a strong shock wave was generated immediately after the explosion and followed by cavitation which occurred due to negative pressure caused by expansion waves originating from the sea surface, that is, the water-air interface.[3] In the field of cavitation, on the other hand, the problem of the bubble-free surface interaction has been studied to mainly obtain some useful information about the reduction of cavitation damage.[4–9] Gibson[10] found an interesting phenomenon, so-called secondary cavitation which was generated around a primary cavity rebounding relatively far from a free surface, owing to the low pressure below the threshold value in the region of concern. The low-pressure generation was reasonably explained as the result of the superimposed effect of the surrounding static pressure, decreasing as the cavity re-expanded, with the tension waves coming from the free surface. Another secondary cavitation can exist in the rebound process of a bubble located relatively nearer to a free surface. The present investigation deals with this phenomenon.

A schematic diagram of the experimental arrangement is shown in Fig. 1. A vapor bubble was generated by focusing a ruby laser with 20 ns pulse duration from below a bubble chamber into tap water at room temperature (297 K) under atmospheric pressure.[8,9] The surface tension of the water was measured as 7.2×10^{-2} N/m. The water was provided into the chamber through a filter with a 5 μm element. The behavior of an induced bubble was photographed with an image converter camera (John Hadland Imacon 790) with a Xe flash of 200 μs pulse duration as a light source. The timing for photographing was controlled with a delay circuit. A pressure transducer (Swiss Kistler 603B) was located 20 mm away from the focal point and only used for measuring the pressure pulse duration which is exactly corresponding to the period of the bubble motion. So, we can evaluate the maximum bubble radius because it is linearly proportional to the period of the bubble motion. That the maximum bubble radius is known enables us to observe the detail of the event. Signals from the transducer were amplified with a charge amplifier and recorded onto a synchroscope.

Figure 2 shows an example of the overall motion of a bubble near a free surface, where the interframe time is 10 μs, the maximum bubble radius $R_{max} = 0.86$ mm, and the initial bubble location from the free surface $L = 0.95$ mm (i.e., $L/R_{max} = 1.10$). We note that the period of the bubble motion is 19% shorter than that of the infinite case. As a free surface is very compliant because of being bounded by air, it can easily move up due to the motion of virtual mass of water while the bubble expands. The free surface continues rising up, whereas the bubble begins to collapse. The upper part of the bubble surface, nearer to the free surface, becomes flat, and finally followed by a liquid jet in the direction away from the free surface.[5,6] We can observe the translational motion of the bubble in the last stage of its collapse. A noteworthy event occurs in the rebounding process of the bubble, that is in the 14th frame of Fig. 2. It is a black band appearing above the bubble and disappears in the next frame. To observe this phenomenon in detail, a

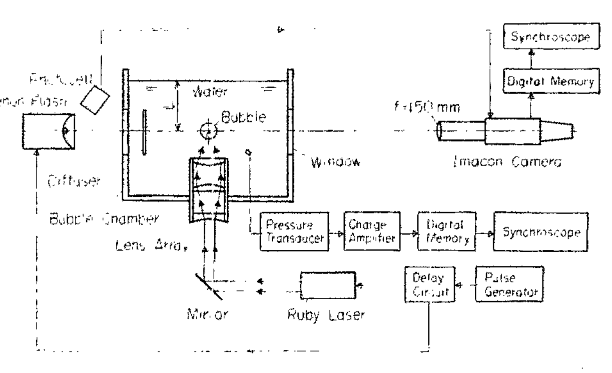

FIG. 1. Schematic diagram of the experimental apparatus.

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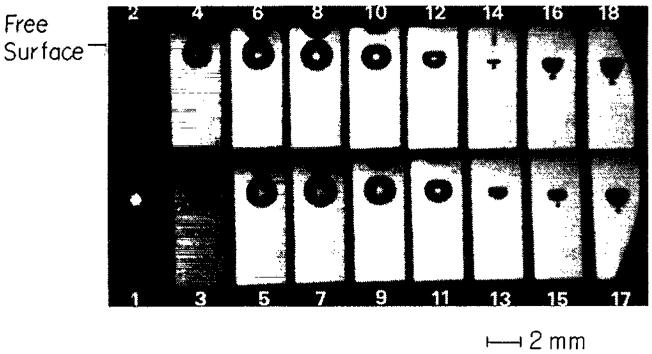

FIG. 2. Overall motion of a bubble near a free surface. The interval between frames is 10 μs. The maximum bubble radius $R_{max} = 0.86$ mm, and the initial bubble location $L = 0.95$ mm ($L/R_{max} = 1.10$).

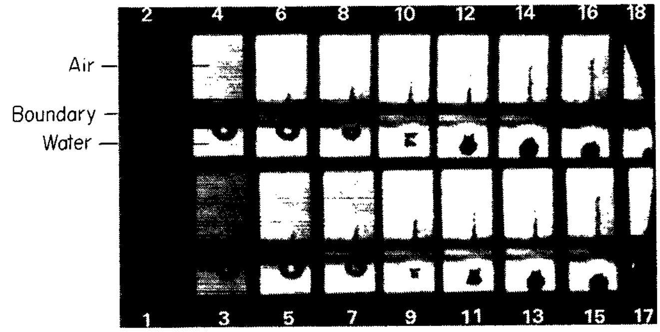

FIG. 4. Rising of a free surface during the collapse and rebound processes of a bubble, which is leaving from the surface. The interframe time is 10 μs.

photograph was taken for a bigger bubble in order to cover the behavior just before and after the first collapse of the bubble. Figure 3 shows an example of this case where the conditions are $R_{max} = 1.67$ mm, $L = 2.36$ mm (i.e., $L/R_{max} = 1.41$), and the interframe time 10 μs. Again a slender substance suddenly appears in the eighth frame and it becomes small with time. Important evidence is revealed in the 12th frame in which the substance is obviously rebounding. Extrapolating two curves concerned with bubble volume versus time which were obtained with considering the volume loss corresponding to the liquid-jet formation inside the bubble for both the collapse and rebound processes and evaluating the instant of the minimum bubble volume from which a shock wave ought to be originated, we can estimate the eighth frame to be 4 μs after the first bubble collapse point. The time of 4 μs seems to be sufficiently long for a spherical shock wave to interact with the free surface that probably keeps rising up. The shock wave is reflected as an expansion wave in the form of a circular contact on the rising free surface, which involves forming an envelope ring as it propagates outwards, that is going towards the center axis. The envelope ring finally concentrates at some part on the symmetric axis, resulting in producing a strong negative pressure where cavitation will surely occur. Another important finding was pointed out

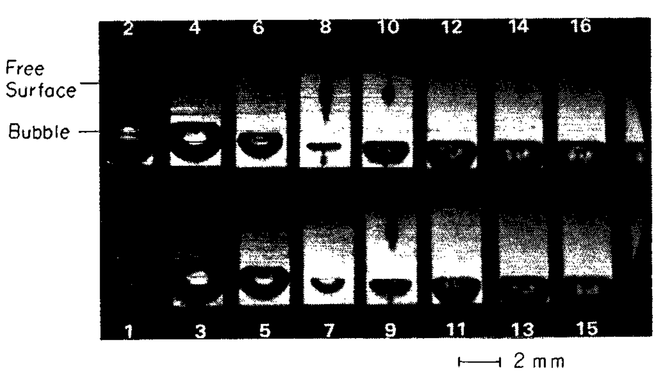

FIG. 3. Detailed behavior of a secondary cavitation generated immediately after the bubble rebound. The interframe time is 10 μs, the maximum bubble radius $R_{max} = 1.67$ mm, and the initial bubble location $L = 2.36$ mm ($L/R_{max} = 1.41$).

by Blake *et al.*[6] from numerical calculation that during the collapse of a bubble near a free surface, the zero dynamic pressure region is formed in water along the symmetric axis, beneath the rising free surface and above the upper surface of the bubble which is moving away from the free surface. Around here liquid particles move in opposite directions, causing tensile stress. The zero dynamic pressure region varies along the symmetric axis depending on the relative distance of a bubble from a free surface. We conclude that the slender substance appearing immediately after bubble rebound near a free surface must be secondary cavitation resulting from negative pressure due to the combined effect of the two physical causes mentioned above, such as the focus of expansion waves at around zero dynamic pressure region.

The next two photographs will be helpful for our consideration on secondary cavitation. Conducting on lighting carefully, we can have a photograph like Fig. 4 in which both a thin spike formed onto a free surface and a bubble moving underneath the surface are straightforwardly visualized, though a water-air interface is unclear. This kind of photograph apparently indicates that a free surface must be greatly deformed during bubble rebound. A more effective photograph is shown in Fig. 5, which was taken by means of the Schlieren method. In this case, we can see only the base of a free surface, in other words the surface corresponding to the original free surface, because of light used

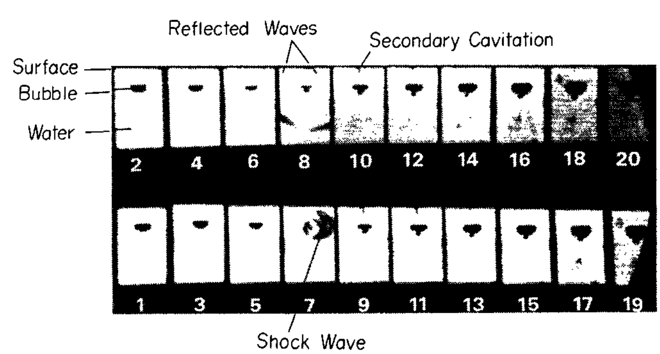

FIG. 5. Schlieren photograph showing the interaction of a shock wave emitted from a bubble with a rising free surface. The interframe time is 1 μs.

being parallel. Shock waves are emitted in the seventh frame where a bubble is rebounding and reflects at the surface in the eighth frame. We notice that the reflected waves are not in one large hemispherical configuration but they consist of small hemispherical waves. This experimental evidence suggests that the free surface is undoubtedly deformed. A secondary cavitation in the form of elongation is visible from the ninth frame.

The authors would like to acknowledge useful discussion with Professor J. R. Blake of the University of Birmingham. They also wish to express their thanks to Mr. N. Miura of the Institute of Fluid Science, Tohoku University for his help in drawing the figure.

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